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# **Aerothermochemistry in Meteoric Plasmas and the Impact of Meteors on the Pre-biotic Evolution of Life**

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Submitted as a report to Science (Jan. 29, 2000)

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The rarefied nature and high Mach number (up to 270) of the flow field of a typical meteoroid as it enters the Earth's atmosphere implies conditions of ablation and atmospheric chemistry that have proven to be as difficult to grasp as the proverbial shooting star. An airborne campaign was organized to study these processes during an intense Leonid shower. A probe of molecular band emission now demonstrates that the flash of light from a common meteor originates in the wake of the object rather than in the meteor head. A new theoretical approach using the direct simulation Monte Carlo technique demonstrates that the ablation process is critical in heating the air in that wake. Air molecules impinge on a dense cloud of ablated material in front of the meteoroid, are partially mixed in, thermalize, and expand beyond the meteoroid head into an extended wake that has the observed excitation temperatures. These processes determine what extraterrestrial materials may have been delivered to Earth at the time of the origin of life.

Accretion of cometary matter has long been of interest in studies of the origin of life [1], but the bulk of incoming matter has been ignored so far. It is in size ranges too small to cause shock chemistry and too large to survive ablation. This lack of attention for common meteors is because physical processes dominated by free molecular flow and high Mach numbers conspire against theoretical and laboratory studies of meteoric plasmas. Factual data rely on remote sensing, to which few modern techniques have been applied.

As part of a larger effort [2] by researchers of seven nationalities on board two aircrafts over Okinawa, Japan, we deployed a new high-resolution slit-less CCD spectrograph for near-infrared and visible wavelengths [3] at the time of the intense 1998 Leonid shower [4]. This was NASA's first Astrobiology mission. The same spectrograph was used again to probe Perseid meteor spectra from a ground site in August of 1999.

Our best spectra probe 1 cm sized meteoroids with entry velocities of 61 km/s (Perseids) and 72 km/s (Leonids), respectively, at altitudes 90-100 km. The spectra cover the wavelength range 580 - 900 nm and are dominated by atmospheric lines of O and N and the first positive bands of  $N_2$ , in contrast to prior studies at shorter wavelengths where spectra are dominated by lines of ablated metal atoms.

The observed lines and bands are surprisingly well matched by the NEQAIR2 radiation model of heated air in thermodynamic equilibrium [5]. In Figure 1 we show the observed Leonid spectra and a simulation that considers all transitions available in NEQAIR. The match implies that the bulk of emission is from gas in near thermal equilibrium, despite the high Mach number flow. The observed ratio of atomic and molecular nitrogen in the Leonid spectrum of Fig. 1 implies a chemical equilibrium temperature of  $4340 \pm 100$  K. The  $N_2$  band contour (and NI lines) of the Perseid of Fig. 2. are well matched by a simulation at  $T = 4300 \pm 40$  K. All values are surprisingly similar to temperatures estimated from the general appearance of the metal atom ablation line spectra:  $4500 \pm 500$  K [6].

The data are precise enough, however, to recognize numerous signs of non-equilibrium. There is excess emission at high  $v$  levels in the  $N_2$  molecular band as a result of the process of recombination. The OI line intensities are not always well matched. Notably, the OI line at 8446 Å is a factor of 3 fainter than calculated in all Leonid spectra and different from laboratory LTE air plasmas [7]. Also, the NEQAIR model with initial 0.03% atmospheric  $CO_2$  predicts CN emission comparable to the first positive  $N_2$  bands, while we do not detect the expected Red System of CN (peaking at 7920 Å), nor the  $\Delta v = 3$  Phillips band of  $C_2$  (near 7760 Å). Finally, the meteors appear much brighter than expected. The implied emitting volume is impossibly large, equivalent to a sphere that is 60 times larger in radius than predicted by initial train radius theory [8].

The source region of the  $T \sim 4300$  K emission was identified using the direct simulation Monte Carlo (DSMC) technique, which was applied to the two-dimensional flow about a 1 cm sized Leonid (density 1 g/cm<sup>3</sup>). DSMC has been developed and applied to a variety of rarefied flows for many years [9], but this is the first attempt to apply the technique to a computation of this type. Two cases were considered: one with no ablation, and one with a simple Brönshten ablation model [10], in which the ablated material is assumed to be magnesium.

In the model without ablation (Fig. 3a), the region of high translational temperature is confined close to the meteor, with a rapid decline of temperatures outward, where multiple collisions quickly stop the accelerated air molecules. Clearly, the plasma in the head provides the near spherical source of radar head echoes, considered in initial meteor

train radius theory [8]. If ablation is included, however, the picture changes dramatically. We find that ablation increases the flow field temperature around the meteor over an extended area in a wake behind the meteor, with elevated values around 5,000 K (Fig. 3b).

The wake is caused by air molecules penetrating the skin of a dense plasma of ablated material in front of the meteoroid, being thermalised, flowing past the meteoroid, and finally expanding into the meteoroid wake. The rotational temperatures are typically less than translational temperatures in the head but they equilibrate in the wake. It is from this (nearly) equilibrated gas that most meteor emission is observed.

Interestingly, the study of fast shower meteors can help clarify bigger picture processes that involve a much wider range of meteoroid masses and entry velocities. The wake temperatures derived from the metal atom emission of many other meteors are in the narrow range of  $3900 \pm 900$  K [11], with no obvious trend with meteor magnitude (mass) or entry velocity. The observed Leonid spectra too do not change significantly with altitude or meteor brightness over the observed range.

Meteors deposit a significant amount of kinetic energy in the upper atmosphere that can go towards aerothermochemistry of interest for nitrogen fixation at the time of the origin of life on Earth [12]. Also, some 40 million tons/year worth of meteoroids [13] deposited organic matter and metallic compounds in a rarefied high Mach number flow at that time.

Our observations show that relevant atmospheric chemistry can occur in two regimes: in the extended wake of the meteors at temperatures of about 4300 K and at the interface layer between impinging air and ablation products at temperatures of about 10,000K [14]. In both cases, the chemistry occurs at higher temperatures and longer timescales than in the 1-D equilibrium models by Park & Menees [15] and does not fully equilibrate.

Unfortunately, no models are yet capable of handling reliably the non-equilibrium chemistry implied by the observations. An important find, however, is that the observed excitation temperatures are close to the dissociation equilibrium of CO. As a result, our chemistry simulation of the meteor plasma in a CO<sub>2</sub> rich Mars-like atmosphere (Fig. 4) results in high yields of potential pre-biotic molecules. The chosen air composition may reflect that of the Early Earth and is certainly the least favorable case for reaction chemistry. Right at about 4200 K is where the production of linear carbon chains such as C<sub>2</sub> and C<sub>3</sub> peaks. In these conditions, small amounts of polycyclic aromatic hydrocarbons are expected to be formed upon cooling, as well as compounds rich in C=O and C-N groups. Such compounds offer numerous chemical pathways to other reduced molecules of potential significance for the origin of life.

Finally, the lack of observed C<sub>2</sub> or CN emission from the combustion of organic matter in the meteoroids suggests that organic compounds may survive as large molecular fragments. Perhaps there is an analogy with the common technique of laser induced desorption of large molecules,

because the ablating material is only momentarily heated and quickly cooled by collisions with air molecules.

Future opportunities to study meteoric accretion will occur during the anticipated Leonid meteor storms of 2001 and 2002 [16] when, briefly, the sky is expected to look again like it did at the time of the origin of life.

*The deployment of the 1998 Leonid Multi-Instrument Aircraft Campaign was made possible by grants from the NASA Astrobiology, Planetary Science, and Technology Programs, NASA Ames Research Center, and the U.S. Air Force, while the spectrograph was developed with support of the NASA Ames Research Center Director's Discretionary Fund.*

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- [3] The slit-less meteor spectrograph used a 600 l/mm grating in front of a 300 mm f/2.8 Nikon lens, for highest possible dispersion, with Kodak No. 24 Wratten gelatin filter to separate the orders and a Pixelview two-stage cooled CCD camera. The camera was set to 0.1s exposure time followed by 1.5s readout time for minimum interference from star spectra. The detector was not intensified to keep the highest possible resolution preserved. Only part of the meteor spectrum was recorded, depending on where the meteor appeared in the field of view. Each spectral line is an image of the path of the meteor on the sky, forming a banded pattern at some angle with respect to the CCD axis. The spectra show the final part of the path when the meteor was most intensely emitting. The short 0.1s integration time suppresses all emission persisting at longer time scales.
  
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### FIGURE CAPTIONS:

Fig. 1.: High resolution spectra of -1 magnitude Leonids at 17:47:06 UT (7100-8500 Å) and 18:08:47 UT (8300-9000 Å), Nov. 17, 1998. The dashed line shows the NEQAIR simulation at 4300 K. The simulation considers pure air (79% N<sub>2</sub> and 21% O<sub>2</sub>) at the standard atmosphere pressure of  $P = 10^{-6}$  atm at the altitude of the meteor (95 km). The spectrum was convolved with a triangular slit function of FWHM = 5 Å, which matches the line width measured on the observed spectra.

Fig. 2. The  $\Delta v = 3$  first positive band of N<sub>2</sub> as resolved in the spectrum of a -1 magnitude Perseid meteor at 00:25:26 UT, Aug. 13, 1999. The blue line shows the NEQAIR simulation at 4300 K, the red line at 4670 K.

Fig. 3: Translational temperature field from a rarefied flow model of a -1 magnitude Leonid meteor at 95 km altitude. Two cases are shown: without ablation (a), and with ablation of Mg atoms (b).

Figure 4: Molecular abundances for equilibrium air plasmas at 95 km altitude ( $P = 10^{-6}$  atm) in a range of LTE temperatures and for an equilibrium Mars-like early-Earth atmosphere of particle number composition O<sub>2</sub>/CO<sub>2</sub>/N<sub>2</sub>/Ar/CO = 0.13/95.32/2.7 /1.6/0.08%.

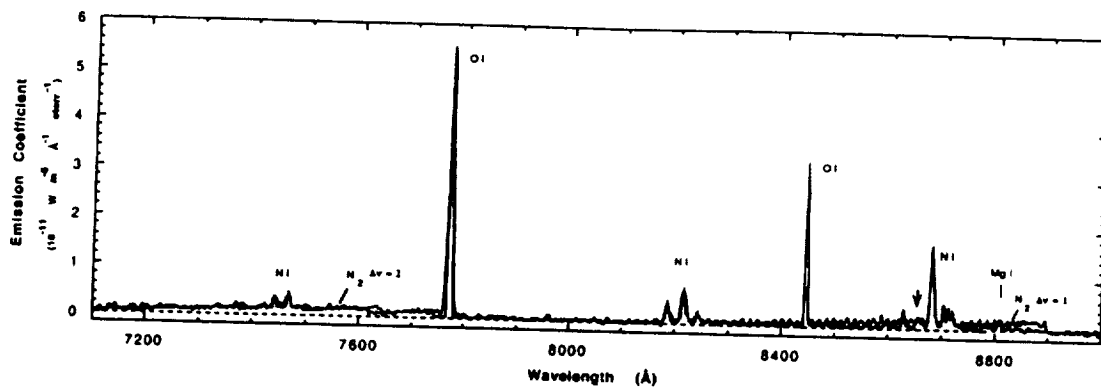


Fig. 1 - Jenniskens et al.

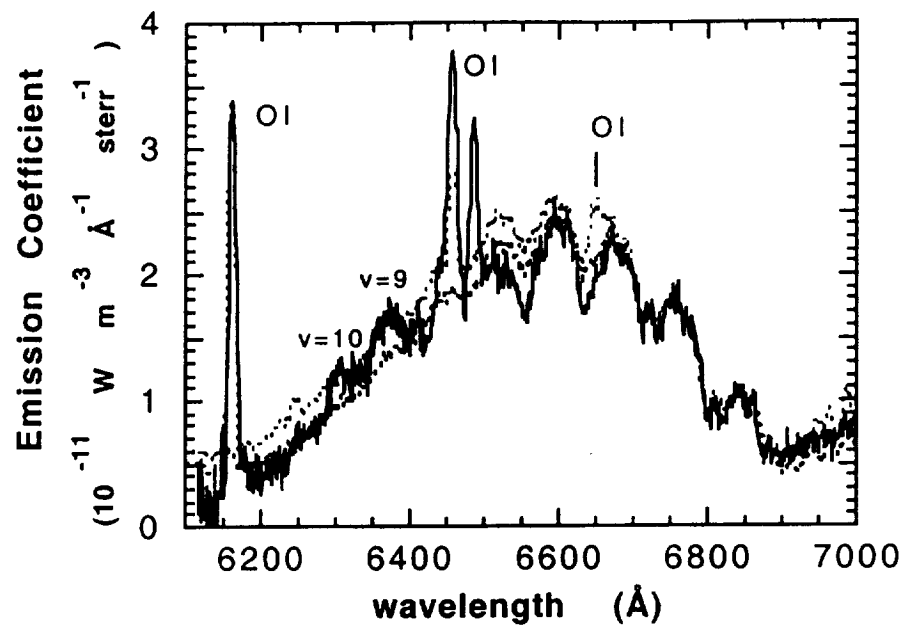


Fig. 2 - Jenniskens et al.

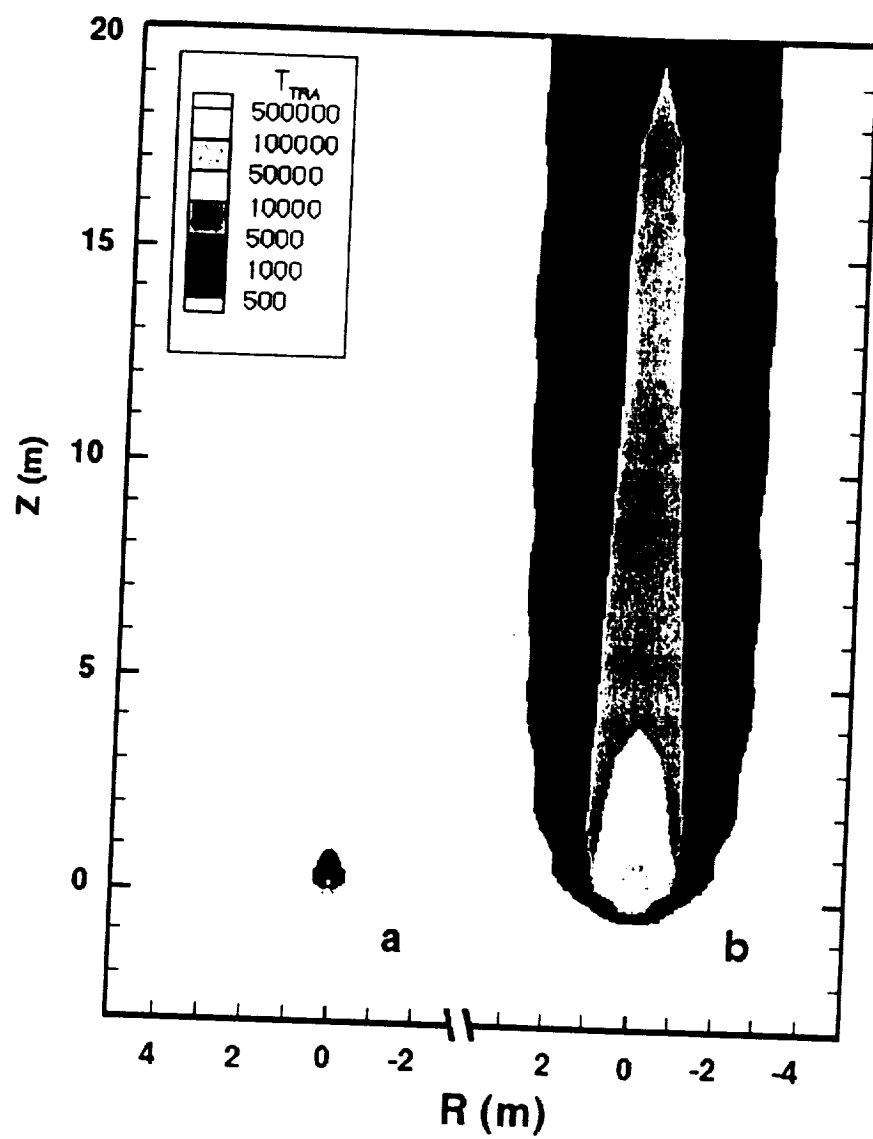


Fig. 3 - Jenniskens et al.

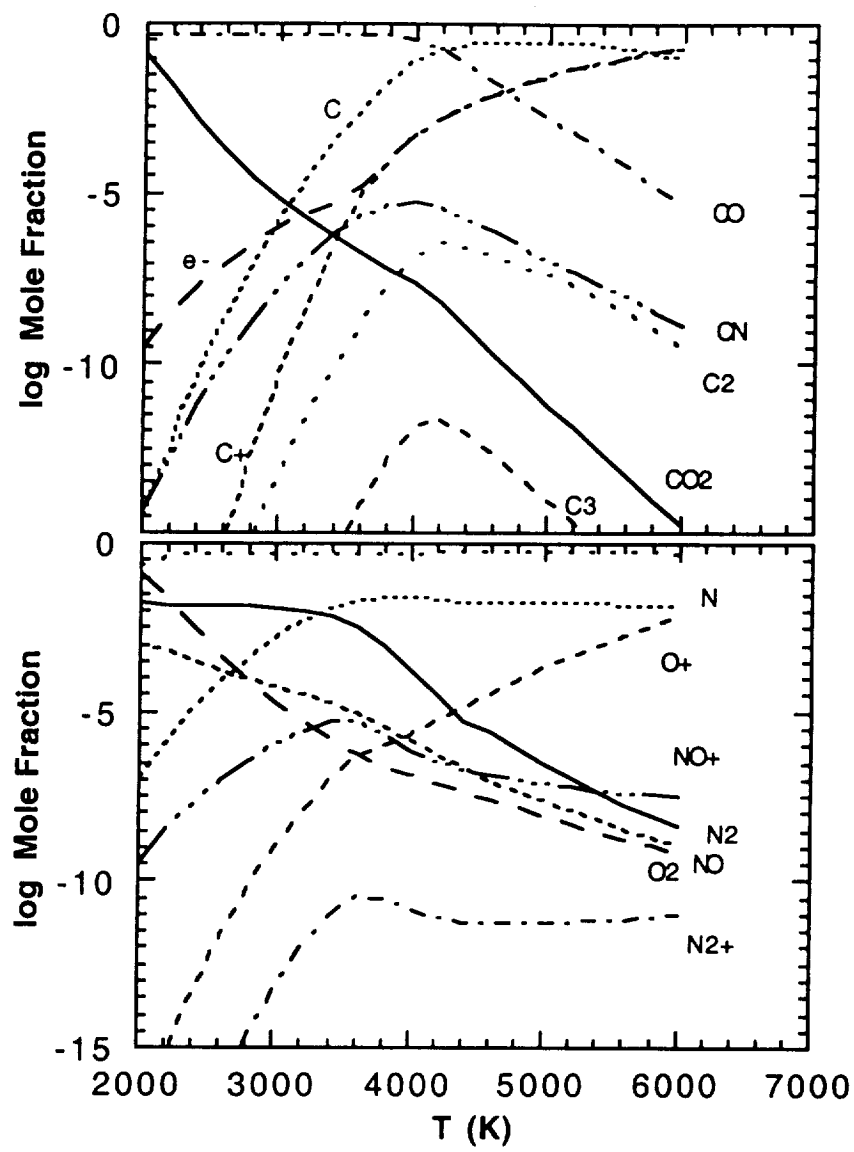


Fig. 4 - Jenniskens et al.

